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Urban Hydroinformatics: Past, Present and Future

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Abstract: Hydroinformatics, as an interdisciplinary domain that blurs boundaries between water science, data science and computer science, is constantly evolving and reinventing itself. At the heart of this evolution, lies a continuous process of critical (self) appraisal of the discipline's past, present and potential for further evolution, that creates a positive feedback loop between legacy, reality and aspirations. The power of this process is attested by the successful story of hydroinformatics thus far, which has arguably been able to mobilize wide ranging research and development and get the water sector more in tune with the digital revolution of the past 30 years. In this context, this paper attempts to trace the evolution of the discipline, from its computational hydraulics origins to its present focus on the complete socio-technical system, by providing at the same time, a functional framework to improve the understanding and highlight the links between different strands of the state-of-art hydroinformatic research and innovation. Building on this state-of-art landscape, the paper then attempts to provide an overview of key developments that are coming up, on the discipline's horizon, focusing on developments relevant to urban water management, while at the same time, highlighting important legal, ethical and technical challenges that need to be addressed to ensure that the brightest aspects of this potential future are realized. Despite obvious limitations imposed by a single paper's ability to report on such a diverse and dynamic field, it is hoped that this work contributes to a better understanding of both the current state of hydroinformatics and to a shared vision on the most exciting prospects for the future evolution of the discipline and the water sector it serves.

Keywords: hydroinformatics; smart cities; smart utilities; resilience; distributed systems; data; analytics; decision support; sociotechnical system; ethics; digital water

1. Introduction

1.1. Hydroinformatics—An Evolving Story

The water cycle is a system characterized by inherent complexity, variation, and uncertainty due to interlinked social, natural and engineered subsystems. Hydroinformatics, as a scientific study of this complex system takes a deliberately interdisciplinary, sociotechnical approach [1], blurring the boundaries between water science, data science and computer science. Despite having its origins in computational hydraulics [2], it, however, does not only concern itself with modelling and decision support, as is often incorrectly assumed. The modern field of hydroinformatics also embraces the social dimension of water cycle management, e.g., social needs, concerns and consequences (including equity, data privacy, ethics, legal issues, etc.). Therefore, hydroinformatics should be viewed as having a horizontal role in integrating water sciences (i.e., hydrological, hydraulic and environmental), data sciences (statistics, stochastics, data driven analytics), computer science and information and communication technologies (ICT) and society [3]. This also positions hydroinformatics as a cross-cutting field of study that underpins the transition of water authorities and utilities from reactive to proactive by leveraging technological advances to achieve to the so-called Water 4.0 state (also named Digital Water or Water Informatics) delivering sustainable and resilient water management.

As a dynamic field of research, hydroinformatics has evolved from the days of hydraulic/hydrologic modelling to an academic discipline with a thriving community of scientists, engineers and practitioners (organized around two professional organizations—the International Association for Hydro-Environment Engineering and Research, IAHR, and the International Water Association, IWA), with its own Journal [4] , specialist groups and biannual international conferences. However, the discipline's network is not restricted to these institutions. It has grown around the world building strong communities and high-profile scientific journals, such as the International Environmental Modelling and Software Society (iEMSs) and their Journal [5] as well as the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI) in the US and their Hydroinformatics Conferences. The discipline and its community run and contribute to educating new generations of hydroinformaticians through a number of professional and university degree courses offered all around the world.

Although it is beyond the scope of this paper to delve into the depths of hydroinformatics philosophy and approaches, the discipline can be thought of as a continuous process of developing and using water data, models and tools, to understand the environment, to engage all stakeholders, and help make decisions that improve society. This is a highly iterative process (Figure 1), because, as also stated in Vojinović and Abbott [6], "*hydroinformatics integrates knowledges from the social and technical domains to create so-called conjunctive knowledges, that are concerned with an understanding of how technical interventions have social consequences and how the resulting social changes in turn generate new technical developments*". This evolving nature of hydroinformatics can also be viewed through the lens of changing communities attending the biannual Hydroinformatics conferences and consequently the transformation in the research focus over a period of 25 years. While the early years attracted mostly practitioners from the mature fields of computational hydraulics and hydrology and those involved in early applications of artificial intelligence methods, the later years' conferences can be viewed as a meeting place of a community of communities, encompassing various multi-disciplinary areas. This widening of disciplinary communities resulted in changes to the scope of the work presented at conferences, for example, from purely technical approaches to managing demand for water to socio-technical approaches where customer engagement is sought through, not only technical means, but also by combining behavioral and data science. Further examples of the changes include the proliferation of real-time modelling and decision methods due to increasing computing power and the availability of data through citizen science and ubiquities sensing. Together, with the drive to open science outputs to a wider audience (via open-source tools and data), to hybridize modelling systems (via integration of physical and data-driven models), and to better visualize data, processes and decisions (via serious gaming, virtual/augmented reality), the community is well-positioned to help humanity address a range of high-impact future real-world water challenges.

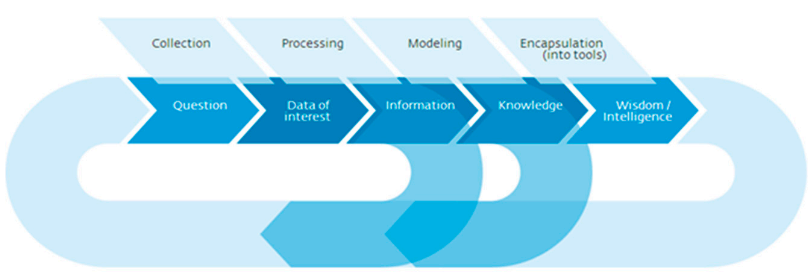

Figure 1. The circular nature of hydroinformatics.

1.2. Aim of This Paper

Hydroinformatics has considerable advances to show across the entire water cycle, however it would be beyond the scope of this paper to include a review of all contributions in the field, thus the focus is limited to urban water issues and perspectives. This is because as urbanization continues to accelerate concentrating ever increasing demands for water services in cities and megacities around the world [7], and as urban water infrastructure is ageing and related investments are lagging behind [8], it is argued that the urban environment urgently needs smarter solutions based on hydroinformatics more than any other domain.

The current state of the art in (urban) hydroinformatics is mapped, proposing a narrative that connects several elements and strands of work together into a coherent whole. This narrative necessarily leaves aspects of hydroinformatics out, and where applicable, references to additional review work is added to assist the reader. Specifically, the paper highlights three main pieces of the hydroinformatics puzzle: Data, analytics and decision support (the last one in both its formal planning/design and societal/communication/engagement sense) in an effort to suggest a way of thinking about the domain and to point towards a promising future.

2. From Theory to Practice

Water systems and services are highly complex [9] as they are tasked to balance water resources with demands through complex interconnected infrastructure. As such, decision making about these systems and services (at strategic, tactical and operational scales) need to be taken within a continuously changing landscape where water quality and quantity are uncertain [10]. These systems are also influenced by climatic changes and human practices water demand patterns are shifting as urbanization continues [11], influencing demands [12] as standards of living rise [13]. Lastly,, environmental legislation and customer expectations are also shifting and with them [14,15], the thresholds against which the water sector's performance is measured also change. This dynamic decision landscape is further complicated by aging infrastructure [16] and the advent of new (disruptive) technologies and concepts.

Figure 2 presents an overview of some of the main technologies and concepts that have emerged in the past few years and are influencing both research and practice in the urban water management field and hydroinformatics specifically. In this necessarily brief and elliptical sketch, new real-time information coming from smart sensors, including smart meters, also in the context of IoT developments, stored and managed through (often cloud-based) information platforms [17,18], allow for the remote monitoring and control of new more distributed interventions in the urban water cycle integrated into (and extending the useful life of) existing centralised systems and networks. This is possible due to, also, new analytics that are developed to exploit and extract value from this new information in view of design, tactical and operational decisions (from locating new technologies, to rehabilitating piped networks to understanding and managing water demands [19]). Part of the value in this improved understanding of subsystem functions is in being able to develop and calibrate whole cycle (socio-technical) system models. They are now increasingly being applied to improve the understanding of the interplays between centralised and decentralised systems as well as the interaction between infrastructure and the end users. These new, more inclusive modelling approaches underpin a more engaging approach to decision support in the form of serious games (SG), and augmented/virtual reality (AR/VR) environments, challenging and disrupting the very way decisions are made in the water sector [20]. The latest developments in artificial intelligence (AI) and machine learning (ML) have already shown that AI/ML enabled software systems can beat human players in complex games, such as chess or Go [21]. Through reinforcement learning, these systems can learn by playing games, which can be a guiding light to developing decision-support systems capable of assisting human water system operators in performing complex operational, tactical or strategic tasks. Similarly, robotic technologies and AI, which have been making great strides in the manufacturing and consumer industries, are starting to find their way to water management, e.g., underground asset inspection [22]. Lastly, the authors argue that with these data, tools and models at hand, the sector is now developing more sophisticated ways of stress-testing new and existing infrastructure, developing new methodological approaches around resilience [23]. In the remaining part of this section, a brief overview of some key literature on the subjects highlighted above is provided and an outline of their current state of art is discussed.

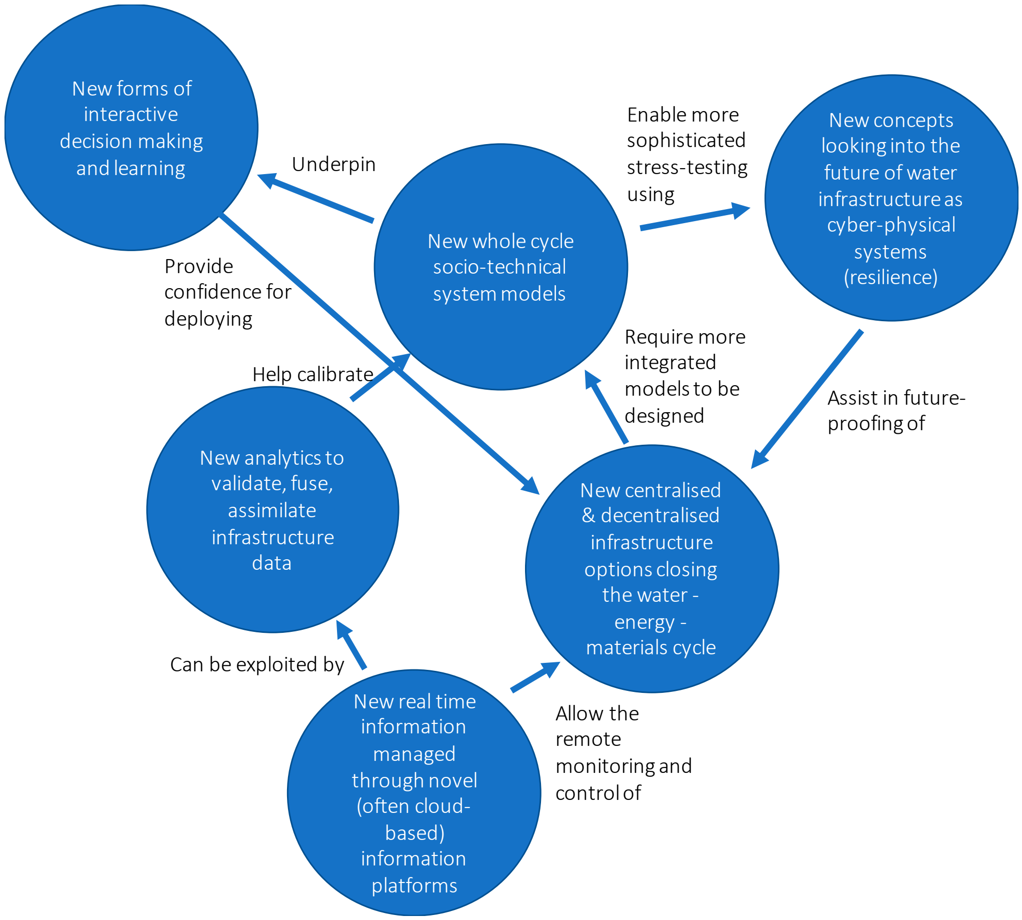

Figure 2. A shifting landscape for hydroinformatics research and practice.

2.1. New Real Time Information

The rapid developments in ICT, leveraged through advances in hydroinformatics, have created the basis for a phenomenal increase in the types and amounts of water-related data collected and analyzed, following the trend (and to some extent hype) of the so-called Big Data currently evident in numerous other fields and sectors [24]. Although the volume of water data currently collected by the sector is certainly unprecedented, attributed to an increasing deployment of dedicated sensors of various types, the data in the water sector cannot really be considered big, at least not yet. Water data are often structured data and do not usually include the main types of unstructured data (such audio, images, video, and unstructured text) that account for 95% of big data at the global scale [24]. A notable (and promising) exception is when crowdsourcing is also taken into account as a means of supplementing data obtained from more traditional sources [25]. The arrival of big data is also coinciding with a strong movement by individuals, learned societies and governments to open data for the benefit of individuals and society in general. The availability and use of open data—that anyone can access, use or share—can also increase opportunities for the collaboration and engagement of stakeholders, particularly in cities. The rise of the 'Smart City' concept, where ICT (and IoT) are used to enhance a city's livability, workability and sustainability, is another factor that impacts on the use of big data in urban water management [26]. The developments in this (growing) nexus between water and ICT (often termed digital water, Water 4.0 or water informatics), allow water companies to now be able to monitor in (near) real time their entire supply and value chain, from the sources to the consumers' tap and then 'downstream' to the wastewater plant. Smart sensors and smart meters (e.g., [27]) are becoming ubiquitous allowing for a substantial increase in coverage (e.g., [28]), resolution (e.g., [29]) and diversity (e.g., [30]) of water-related information, including water quality [30–32], which has long been the most difficult water characteristic to reliably monitor remotely. Interestingly, new water related information is not only collected by smart sensors and devices. It is also increasingly collected by the citizens/water users themselves. For example, the paper-based water quality sensor and smartphone that was used in Sicard et al. [33], or work by Farnham et al. [34] on using citizen-based water quality monitoring for combined sewer overflows.

2.2. New Distributed Infrastructure Deployment

The increasing availability of information (and remote-control capability) allows the sector to seriously consider and gain confidence in re-engineering its water management practices [35]. This can be achieved also by deploying in large scales more promising, distributed alternatives to water service provision (from treatment to separation and from reuse to drainage, see for example Larsen et al. [36]) that have hitherto been reserved for research/pilot environments. Although a review of these technological developments falls outside the scope of this paper, it is argued that their advent is both enabled by new advances in hydroinformatics (in both the hardware and software sense) and enables interesting hydroinformatic developments in the analytics, modelling and decision contexts. An example of this interplay is evident, for example, in the case of distributed water reuse technologies termed sewer mining [37]. Here, novel treatment solutions emerged, that required advanced monitoring and control systems to become deployable in remote locations [38]. This in turn, led to a need for modelling and optimisation tools, able to support the optimal location of sewer mining units in large sewerage networks [39]. The availability of the sewer mining technology as an intervention option, then meant that integrated models had to include them as options for decision makers [37]. This positive feedback is typical of the way hydroinformatics evolves in a dialectic relationship between the discipline and the water sector.

2.3. New Analytics

To make sense of this increasing amount of information, research and practice have made significant progress towards better analytics, including but not limited to those: (i) Capable of extracting valuable information from the data (from smart alerts to customized advice for water users); (ii) performing better stochastic simulations to improve the ability to produce longer timeseries (based on observations) for long-term scenario development and stress-testing; (iii) performing advanced optimisation to identify better solutions in this information richer environment; and (iv) providing novel ways of visualizing and understanding the decision tradeoffs within complex decision spaces. Examples of these new analytics, include AI/ML analytics for proactive management of water distribution systems (including burst detection) demonstrated in UK case studies [40,41], asset deterioration assessment [42], as well as the use of deep learning techniques for defining novel control strategies that are more robust against cyber-attacks of water distribution systems [43]. Examples also include recent work on using smart meter readings to parametrise residential water demand models [44] as well as the methods and tools developed to investigate the properties of these timeseries at fine timescales [29]. Based on this growing body of work, we are now in a position to assess for the first time if smart meters are effective in water demand management (see for example the review by Sønderlund et al. [27] based on 21 relevant reports and publications) or at least pinpoint the additional information needed to make this transition, including the information content, granularity, frequency and method of delivery etc.

However, getting better historical data is only part of the story. Additional work in stochastics is enabling hydroinformatics to develop simulated timeseries that explicitly represent each process of interest with any distribution model and hence conserve all of the characteristics of historical datasets (e.g., [45]). These longer timeseries can be used to drive hydroinformatic models of complex hydro-systems to better account for relevant uncertainties. However, this substantially increases the (time) burden for optimisation. Recent attention to 'optimisation on a budget' [46] shows how surrogate strategies can be employed to allow for less evaluations of expensive objective functions in evolutionary optimisation. Other authors have also focused on the challenging problem of optimal design under uncertainty and developed optimisation algorithms that exploit the concept of 'real options' [47], thus introducing flexibility into the long-term design for water systems [48]. Although an overview of the developments in optimisation is outside the scope of this paper, this is one of the most prolific fields in hydroinformatics to date. The interested reader is pointed towards an overview of this dynamic field, with a focus on water distribution networks, included in Mala-Jetmarova et al. [49] and in Maier et al. [50] for a more general overview of optimisation in water resources in general. Lastly, it is worth pointing out that developing new algorithms does not necessarily lead to better understanding or decision making. Recent attention to analytics for advanced visualisation of decision spaces suggest that developing visual analytics to explore the decision space in multi-objective (e.g., [51]) or in multi-stakeholder problems [52] is both important and necessary.

2.4. New Whole Water Cycle Socio-Technical System Models

The industry's interest in exploring new options for infrastructure provision (incl. new more distributed options discussed above) is driven in part by the process of aging infrastructure and the resulting investment gap [16]. The interest has also prompted the development and application of whole (socio-technical) system models [53] that attempt a more direct investigation of the interplay between centralized and distributed infrastructure solutions. Furthermore, the focus is also shifting towards the (often ignored) interplay between infrastructure and users (as also argued persuasively in the context of socio-hydrology by Sivapalan [54]). This integration is currently being delivered (mostly) around three axes:

- Integration between centralised and decentralised solutions and (often also) between water infrastructure and urban fabric growth in a common (whole system) modelling environment. Indicative work in this context includes the Aquacycle model [55], the Urban Water Optioneering Tool (UWOT, see Rozos and Makropoulos [56]), UVQ [57] as well as the Dance4Water model [58], to name but a few. For an overview of key models as well as a discussion on the degree of integration, the reader is referred to Bach et al. [59]. These more integrated models, sometimes termed metabolism models (e.g., [60]) are increasingly being used to evaluate alternative pathways for the evolution of water systems under uncertainty, opening up the possibility of looking at a much wider palette of options than was possible with more traditional hydraulic-only models.
- Integration between natural and engineered infrastructure systems and user interactions. This is a growing area of work, which also typically includes the explicit modelling of additional flows (e.g., the nexus between water, energy and material flows within an urban environment). Although approaches to this integration vary widely, these are based primarily on: (i) System dynamics (SD) and/or Bayesian belief networks (BBN); and (ii) agent-based models. Recent examples of the former types include Sahin et al. [61], Baki et al. [62] and Chhipi-Shrestha et al. [63]. In this context, Zomorodian et al. [64] provide an overview of SD applications for water management, while Sušnik et al. [65] provide a comparison between SD and BBN models for water management. Recent examples of the latter type include work by Kanta and Zechman [66], Berglund [67] and Koutiva and Makropoulos [68]. The power of these modelling approaches is that they enable the explicit integration of the socio-economic system into the modelling framework, which is especially important when looking into policy and end-user driven interventions, such as water demand management, water markets, innovation uptake etc.
- Integration between the physical and cyber layer of water systems. This attempt on modelling integration represents a recent development, consistent with the move towards conceptualising water systems as a cyber-physical infrastructure. This conceptualisation, advocated already 10 years ago by Edward A. Lee [69] for a range of infrastructures, is currently being operationalised in the form of integrated simulation environments for the cyber and physical layers of a water system and their interactions [70–72]. Although this work is still not rolled out in an operational

sense within water companies, it is argued that it will become more important in the next few years, as part of a risk management approach for both cyber and physical risks.

It is important to note here that in support to these more integrative explorations, the hydroinformatics community has been developing and demonstrating: (a) Integrated modelling frameworks [73,74]; (b) models as services, often based on open source solutions [75]; and (c) cloud-based modelling systems [76,77], sometimes coupling both local model components and remote web services [78] in an effort to reduce the overhead required to create an integrated model in the first place and make their explorative power more accessible to the water research and practitioner communities.

2.5. New forms of Interactive and Immersive Decision Making

The multi-faceted, multi-discipline and increasingly more inclusive multi-stakeholder nature of water management considerations (and environmental management in general [79]) have given rise to new ways of setting the questions, visualizing potential results and experiencing system performance under different stresses. These ways include Serious Games [80], augmented/virtual (or mixed) reality (AR, VR, MR) and their combinations that enable a different level of immersive, playful experience of problems, options and decisions that can be used in various contexts, including operational, strategic and stakeholder collaborative decision-making. The basic idea of these (relatively new) approaches is that practical water and environmental challenges (and options to address them) can be better understood through a more direct experiential approach. These game-based learning approaches improve critical thinking, creative problem solving and teamwork [79]. They also allow stakeholders to experiment with decisions and outcomes in a safe and fun environment.

Work by several authors is currently finding its way into practical applications, engaging water stakeholders in collaborative decision making for such diverse fields as urban flood management [52], water resources management [81,82] and integrated asset management [83]. At the same time, augmented reality applications (including applications in handheld devices and smartphones) have begun to be actively used in infrastructure inspection and rehabilitations (see for example the Vidente application reported in Schall et al. [84]). The significant potential for this technology is especially evident in cases where infrastructure is underground as in the case of water distribution and sewerage networks. These applications typically superimpose data from GIS systems (such asset databases) or even data from simulations on real world views. This linking of spatial/georeferenced information directly on the real-world entities that they characterize, greatly facilitates the use of relevant data during field work (e.g., asset rehabilitation, water quality monitoring). As such, it ensures increased efficiency in maintenance activities, as well as increased understanding and learning in educational field trips and field-oriented stakeholder engagement processes (e.g., stakeholder visits in innovation demonstration case studies). An example of the latter is students participating in the EcoMOBILE project [85], who used an augmented reality application, as part of a field trip to an ecologically important lake. The virtual information was overlaid on the physical lake including hotspots—guiding students in collecting water quality measurements—but also increasing their understanding of underlying processes. It could be argued that such an increased (and more importantly shared) understanding between stakeholders, makes for a good basis for more inclusive, consensus-driven decision making.

2.6. New Design Concepts and Strategies

The availability of new ubiquitous data, advanced analytics and more integrated modeling frameworks is allowing the sector to perform more realistic stress-tests of water infrastructure (in its physical and cyber-physical sense) to help improve its performance under uncertainty. This activity is currently pushing the discipline's methodological boundaries into developing and applying novel design concepts driven to a large extent by cities worldwide demanding realistic risk management under uncertainty within a context of limited new investments (see for example the 100 Resilient

Cities network supported by the Rockefeller Foundation [86]). These efforts are, recently, centered mostly around the challenging concept of resilience and the development of methods, metrics and tools to assess the resilience of urban water systems. Notable examples include models and tools developed by Irwin et al. [87], Butler et al. [88], Klise et al. [89], Makropoulos et al. [8], Kong et al. [90] as well as Sweetapple et al. [91]). Although a discussion on resilience per se is outside the scope of this paper, we note that this growing body of work, focusing on the highly interdisciplinary and multi-stakeholder context of resilience [92] is an important manifestation of the sociotechnical nature of hydroinformatics. The need to understand resilience emphasizes the role of hydroinformatics as an interface between science and policy, between water systems and urban processes as well as between technology, society and the environment.

3. Sky Is (Not) the Limit

This overview of some of the most exciting developments in hydroinformatics today, may give the impression that most of the important tasks are behind us. This, however, could not be further from the truth. As the discipline is, by definition, linked to and influenced by developments in the dynamically evolving IT sector, with every new development come new challenges and also new opportunities. Although the details of what can happen next are by virtue of this dynamic evolution, hard to predict, some of the most important trends are already visible. In an effort to summarise these future trends, four activity lines towards a hydroinformatics roadmap have been proposed below:

3.1. Tapping into the New Data Landscape

The proliferation of smart systems (including developments in the smart city and more generally the IoT arena) mean that data become more ubiquitous—although work on novel water quality sensors is still needed (see ideas on using graphene for heavy metal detection [93]). However, as more data from different sources become available the issue of standardization becomes vital. This is because standardization allows the pulling together and combined exploitation of data coming from different sources and different data providers, both within a utility but also potentially across multiple utilities, reaching the critical mass of data required to categorize water data as big data and, in turn, unlock the true potential of big data analytics. As such, data standardization, in terms, for example, of metadata, standardized markup languages (like the Open Geospatial Consortium's (OGC) WaterML [94], controlled vocabularies and ontologies [95–97] inevitably play a key role in bringing information and analytics together. Due to their importance in an IoT and related telecommunications contexts, the most successful of these standardization efforts will probably not be initiated within the water domain per se, but rather within smart city, smart home and smart industry contexts, growing towards water, energy and other utility sectors. A case in point is the work by the European Telecommunications Standards Institute (ETSI) and its Smart Appliance REFerence (SAREF) ontology [98], which is currently being expanded [99] towards energy and water, with obvious implications for smart water meters, smart(er) water consuming devices and domestic water demand forecasting and management. Another important development in this field, worth highlighting is FIWARE [100], a curated framework of open source platform components that aims to accelerate the development of smart solutions, including transport, energy, as well as more integrative smart city solutions. FIWARE has already been used to develop interesting examples of interoperability for smart agricultural water management [101] and is now expanding [102] also towards urban water management at different scales. Data quality control and validation (potentially in a distributed way, closer to the data collection itself, see for example developments in edge analytics [103]) and improvement of data access (including data sharing and open data [104]) is also expected to be at the heart of the next steps in hydroinformatics.

With this critical milestone completed, the industry may be able to exploit new developments that allow the industry to get new insights out of large, heterogeneous databases and leverage progress on AI, such as deep learning [105], from the ICT sector, to extract information, develop more accurate forecasts and offer customized services to end users. New opportunities afforded by leveraging the power of AI on larger (and more real time) water datasets, include discovering new causal relationships from data already collected to improve predictive ability, e.g., in infrastructure maintenance, water demand management or emergency response. It may also allow for progress into data assimilation techniques that couple models to field data in real time. Field data from different sources and with different uncertainties is expected to be used in combination with models, thus greatly increasing current abilities for pro-active management of water systems. This new data may also increasingly come from the customer/citizen side, where data crowd-sourcing tools will play an increasing role in collecting real time information [25] as well as in gauging public opinion towards water relevant issues (e.g., water reuse attitudes mined from micro-blogs [106]). These (significantly increased) data streams may range from data collected by smartphone embedded sensors, to information posted on social media, to data collected by, soon to be available, autonomous vehicles —cross referenced and linked to open environmental data, utility sensors and remote sensed information from new satellite networks (like NASA's Surface Water and Ocean Topography (SWOT) mission scheduled to start by 2021 [107].

3.2. Getting More Out of Existing Models

This activity line, is expected to provide the sector with more advanced optimization (including smart model calibration under uncertainty and noise), new ways of model integration (with databases and other models) as well as with real time data (including IoT sensors) to form digital twins of utilities. The concept of digital twins, where the data from the IoT sensors are seamlessly linked with asset management information and both support and are supported by models of the system's operations, recalibrated and updated in real time, across the complete value chain from water resources to customers, is expected to become possible in the near future. This ambition, of a complete integrated digital picture of a water utility may appear far-fetched at this time, but is a future in the making, judging from the interest and investment already underway in forward looking cities, such as Amsterdam [108] and its water utility (Waternet). Necessarily, this process shifts online much of the computing infrastructure for water utilities, with cloud computing for water services and software-as-service becoming the norm. This trend, however, is not without its challenges as is discussed in the following sections.

3.3. Planning for More Resilient (Cyber-Physical) Systems and Services

Armed with new data and models, the sector may also work more on model integration and higher abstraction level modelling/model coupling, where whole system strategic models—potentially linked to digital twins—can be used as real-time control, forecasting and scenario planning tools in a collaborative and inclusive way.

This direct coupling between the physical system and related infrastructure and the controlling cyber layer (from sensors to models to actuators) is expected to afford new opportunities for increased efficiency of water infrastructures throughout their lifetime, from design to building to operating. It would allow, for example, their real time control, with data from multiple sensors being continuously integrated within living models of the physical environment and the infrastructure. Furthermore, it would enable moving significant parts of these calculations to the edge [103], enabling precise and pro-active actuation of pumps, valves, sluice gates, for applications, such as flood forecasting and control [109,110], managing combined sewer overflows [111] and urban water management in general [112].

In this context of ever increasing integration between the physical and the cyber sides of water infrastructure, a growing focus on cyber-physical systems risk assessment and threat modelling (e.g., [71,72]), is expected to become more central in water company preoccupations. Cyber-physical modelling can help the sector manage emerging cyber-physical risks, especially in the context of digital twins. In the same vein, it is suggested that work on modelling cascading effects between water systems and other infrastructures may also move from the research environment [113] to the operational environment of the sector. The move may also involve other water and crisis management stakeholders at national and international levels.

3.4. Training, Engaging and Communicating

Lastly, significant advances in rethinking the way decisions are made (from the strategic to the operational) are expected. These changes in decision-making will be catalyzed through technologies that allow for more immersive and playful experiences of the decision landscape, such as Serious Games coupled with AR and VR (or mixed reality) applications and environments. The disruptive potential of such a technology shift cannot be overstated, potentially influencing everything, from immersive scenarios planning, including crisis management training, to pipe rehabilitation, innovation uptake and water education. This last point brings us, however, face to face with an important challenge: What is the form of education and indeed the skillsets required by new hydroinformaticians to be able to benefit from, engage with and ultimately help evolve this dynamic field? Popescu et al. [114] have already correctly identified this challenge some time ago, when they suggested that hydroinformaticians need to master a subject matter that is *"increasing far more rapidly than the ability of engineering curricula to cover it"*. Indeed, as if water science was not demanding enough, the domain experts also need to be fluent in data science (from statistics to machine learning) and computer science (from information theory to hands-on software development and user interfaces design). They also need to engage with topics ranging from decision theory to social science to ethics and philosophy of science. Popescu et al. [114] argued that flexibility is key here, delivered through modular design and blended forms of learning with face to face courses supplemented with online courses allowing participants to invest in deepening their knowledge in diverse areas in a more customized pace. Clearly these requirements point towards hydroinformatics as a postgraduate rather than an undergraduate course. Actually, Abbott et al., [115] used the term participant rather than student explicitly to highlight a prerequisite of solid undergraduate education in relevant fields and indeed hands-on experience before embarking in such a multi-disciplinary course. They also persuasively argued that the educational challenge posed even after this prerequisite is met, suggests another important subject for future hydroinformatics research, that is, research into the educational and training aspects of the domain. In that context, hydroinformatics may benefit from the emergence of the more immersive and playful approaches and technologies discussed above, not the least due to the active (experiential) engagement (in view, for example, of rapid developments of natural user interfaces [116]) and hazard-free, learning by doing aspects that these approaches afford. This promise, however, implies an important, additional and often neglected prerequisite: As Richert et al. [117] would argue tomorrow's hydroinformatics academics need themselves the technological competencies to allow them to both design and create these immersive environments and the training in digital coaching and joint problem solving in virtual worlds to be able to use them in meaningful and educationally productive ways. It is suggested that this prerequisite can only be delivered through new multidisciplinary forms of collaboration around education per se, both within universities and between universities and research centres and technology providers for an interesting example of emerging forms of multi disciplinarity in education see for example: [118].

4. Some Words of Caution

Although these developments can have enormous societal and technological benefits, they also raise security, privacy, legal, and ethical concerns [25].

The increased dependency of water utilities on ICT to carry out their mission and functions, as well as the tendency to provide interoperability and connect these traditionally closed systems to the Internet, opens them up to, as yet unheard of, cyber threats. A case in point is Maroochy Water Services in Australia, probably the most well-known cyber-attack in the water sector, where over a three-month period in 2000 a disgruntled former contractor took control of over 150 sewage pumping stations and released one million litres of untreated sewage into the environment [119]. Furthermore, the prospect of a large number of smart water meters being installed at customer homes, thus connecting them to the utility ICT systems, raises also a possibility of the wider water infrastructure becoming vulnerable to scalable network-borne attacks.

By the very nature of smart systems, customers adopting them share detailed information about their water usage with the utility, which is then used to better assess the demand and manage the entire system. This information sharing potentially exposes customers to privacy invasions with the main concern being the limited control over personal data by an individual, which can result in a range of negative or unintended consequences. Legal considerations relating to privacy and data protection with respect to services or applications created using customer water usage data (particularly valuable when combined with personal data), has been given insufficient attention in the literature [120]. It is, therefore, positive that the new EU General Data Protection Regulation (GDPR) [121] provides a framework for data protection and privacy for citizens. The regulation deals with the risks of accidental or unlawful destruction, loss, alteration, unauthorized disclosure of, or access to, personal data transmitted, stored or otherwise processed. The regulation's application will inevitably open up new questions and challenges which will need to be addressed, but it is important that this conversation is progressing.

Last, but certainly not least, smart systems as surveillance-enabled technologies as well as AI-based decision making, raise issues of privacy, fundamental rights, ethics and responsibility in technological innovation [122]. The need for rethinking, spelling out and agreeing upon the ethical principles on which these technologies is expected to be based [123] has never been more pressing. This is a challenge, not only for technology (and the safeguards it needs to put in place) but perhaps more importantly for ethics and the humanities that need to pick up the challenge and update their theories, methods, vocabulary and technology to make sense of and proactively manage the potential implications to society from a pace of technological development never seen before.

5. Conclusions: A Bright Future with Some Caveats

This study has presented a summary of the dynamic evolution of hydroinformatics, as a discipline at the interface between water science, data science, computer science and technology on the one hand and society on the other. In so doing, the authors have highlighted exciting advances in new real-time information; new analytics developed to extract value from this new information; novel whole cycle (socio-technical) system models that are calibrated on these new datasets; new more immersive approaches to decision support; more sophisticated ways of stress-testing new and existing cyber-physical infrastructure to improve its resilience. Four activity lines of research have also been proposed, coming up on the horizon (tapping into the new data landscape; getting more out of existing models; planning for more resilient systems and services; training, engaging and communicating). The authors suggest that these activity lines support a virtuous cycle towards more resilient water systems and services. It is further argued that their confluence can drastically change both the form and function of water services and the infrastructure that provide these services in the not too distant future—for the better—provided that important challenges around privacy, fundamental rights, ethics and responsibility in technological innovation are seriously and urgently addressed.

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